GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

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THOMPSON RAMO WOOLDRIDGE INC.
CLEVELAND, OHIO

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GENERATION OF LONG TIME CREEP DATA OF REFRACTORY ALLOYS AT ELEVATED TEMPERATURES

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FOREWORD

The work described herein is being performed by Thompson Ramo Wooldridge Inc. under the sponsorship of the National Aeronautics and Space Administration under contract NAS-3-2545. The purpose of this study is to obtain design creep data on refractory metal alloys for use in space power systems.

The program is administered for Thompson Ramo Wooldridge Inc. by E. A. Steigerwald, Program Manager. J. Sawyer is the Principle Investigator. H. Philleo and R. Ebert contributed to the program.

ABSTRACT

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Creep data are presented for tungsten, tungsten-25% rhenium, TZM molybdenum alloy and AS-30 columbium alloy with photomicrographs of the microstructure before and after test. On the basis of the current test results, the creep strength of tungsten is less than that of tungsten-25% rhenium sheet alloy at 3200°F. In the case of turbine alloys at 2000°F, preliminary tests show that the TZM alloy in the forged condition has a greater creep strength than cross-rolled AS-30 plate material.

Author

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INTRODUCTION

The object of this program is to obtain long-time creep data on selected refractory alloys which have potential use in advanced space power systems. The equipment design and the description of the test methods have been presented in previous quarterly reports.

A large number of the vacuum chambers have shown small leaks in the cold wall welds. As a result, extensive reworking has been performed. At present eleven units have been repaired and testing of the currently available alloys is being conducted in five of the chambers. The purpose of these tests is to screen the alloys on the basis of creep resistance and to select stress levels which will produce useful design data in 10,000 hour tests.

CREEP TEST RESULTS

The test plan consists of conducting tests aimed at determining the relative creep behavior of five turbine alloys in the temperature range between 2000°F and 2200°F and three cladding alloys at 3200°F. The turbine alloys selected for evaluation in forged disc or rolled plate form were: columbium-base alloys, AS-30 and Cb132M; molybdenum-base alloys, TZM and TZC; and ST222, a tantalum-base material. The cladding alloys which are to be tested as 0.030" sheet include: arc-cast tungsten, arc-cast tungsten-25% rhenium alloy, and Sylvania A alloy. At present the AS-30, TZM, TZC, tungsten and tungsten-25% rhenium have been received. The processing history of these alloys is presented in Appendix I along with dimensions of the test specimens and the orientation of the specimen blanks relative to the working direction of the as-received material.

The available creep test data and the chemical analyses of the alloys are presented in detail in Appendix II.

The test procedure involves obtaining a vacuum of 10^{-10} Torr or better at room temperature, then heating the specimen at a rate so that the vacuum never is more than the 10^{-7} range. The specimen is then held at temperature for approximately two hours prior to load application. During the initial stages of the test some specimen contraction is often observed due to a slight temperature decrease produced by the increased grip contact and the resulting increase in heat conduction. As the test proceeds, the vacuum continuously improves into the 10^{-8} - 10^{-9} scale.

The initial creep tests are being conducted at three stress levels with the end-point criteria being a total extension of 1% in the turbine alloys and 5% in the cladding material. The ultimate goal in the screening tests is to obtain this degree of extension in approximately 1000 hours. On the basis of these evaluations, one turbine and one cladding alloy will be selected for 10,000 hour tests.

Tungsten-25% Rhenium

In the last quarterly report creep data were presented for a test on recrystallized tungsten-25% rhenium at 3200°F with a stress of 5,000 psi. Under these conditions a 5% creep level was reached after 37 hours. A second test at 3200°F using a stress of 3,000 psi produced 5% creep after 97 hours. The creep curve for the test at 3,000 psi is plotted in Figure 1 along with the results previously obtained at 5,000 psi. Since a test of 1000 hours duration with 1-5% creep was desired, the data were plotted on a log-log basis in Figure 2 and the 2% creep level extrapolated to 1000 hours giving a stress of 500 psi. Using this value, a test of tungsten-25% rhenium sheet was run at 3200°F and the results are shown in Figure 3, page 5. Figure 3 also contains an insert which presents data obtained during the first hour. The test was discontinued after approximately 250 hours due to a slight leak in the cold wall which caused the pressure to rise into the 10^{-6} Torr range.

A metallographic examination was made of the tungsten-25% rhenium alloy both before and after test. Characteristic microstructures of the tungsten-25% rhenium alloy in the as-received condition are shown in Figure 4, page 6. A photomicrograph of the edge of the sheet parallel to the rolling direction is not shown since it exhibits the same microstructure as the edge perpendicular to the rolling direction. Prior to load application the specimens were recrystallized for approximately two hours at the test temperature. After testing at 3200°F, all specimens were found to be thermally etched revealing large recrystallized surface grains, Figure 5, page 7. The appearance of the microstructure after polishing and chemical etching, also shown in Figure 5, is comparable to the thermally-etched surface.

Chemical analysis of the tungsten-25% rhenium alloy was made after the 97-hour test, and the results are given in Appendix II, Table VIII. No general conclusions relative to changes in composition will be presented until data from the complete test sequence are available.

Tungsten

Creep tests at 3200°F were conducted on recrystallized tungsten sheet using applied stress levels of 3,000 and 400 psi. The data are plotted in Figures 6 and 7 (pages 8 and 9) and presented in detail in Appendix II, Tables III and IV. At 3,000 psi, 5% creep was attained in approximately 30 hours while at a stress of 400 psi the total elongation in 714 hours was only 0.12%. The test was terminated at this time due to a slight leak in the cold wall weld zone.

The microstructure of the tungsten sheet in the as-received condition, Figure 8, shows the deformed grains in the edge of the sheet perpendicular to the rolling direction and "pancaked" grains in the surface of the sheet. After testing, the specimen had the characteristic recrystallized grain morphology, Figure 9, page 10.

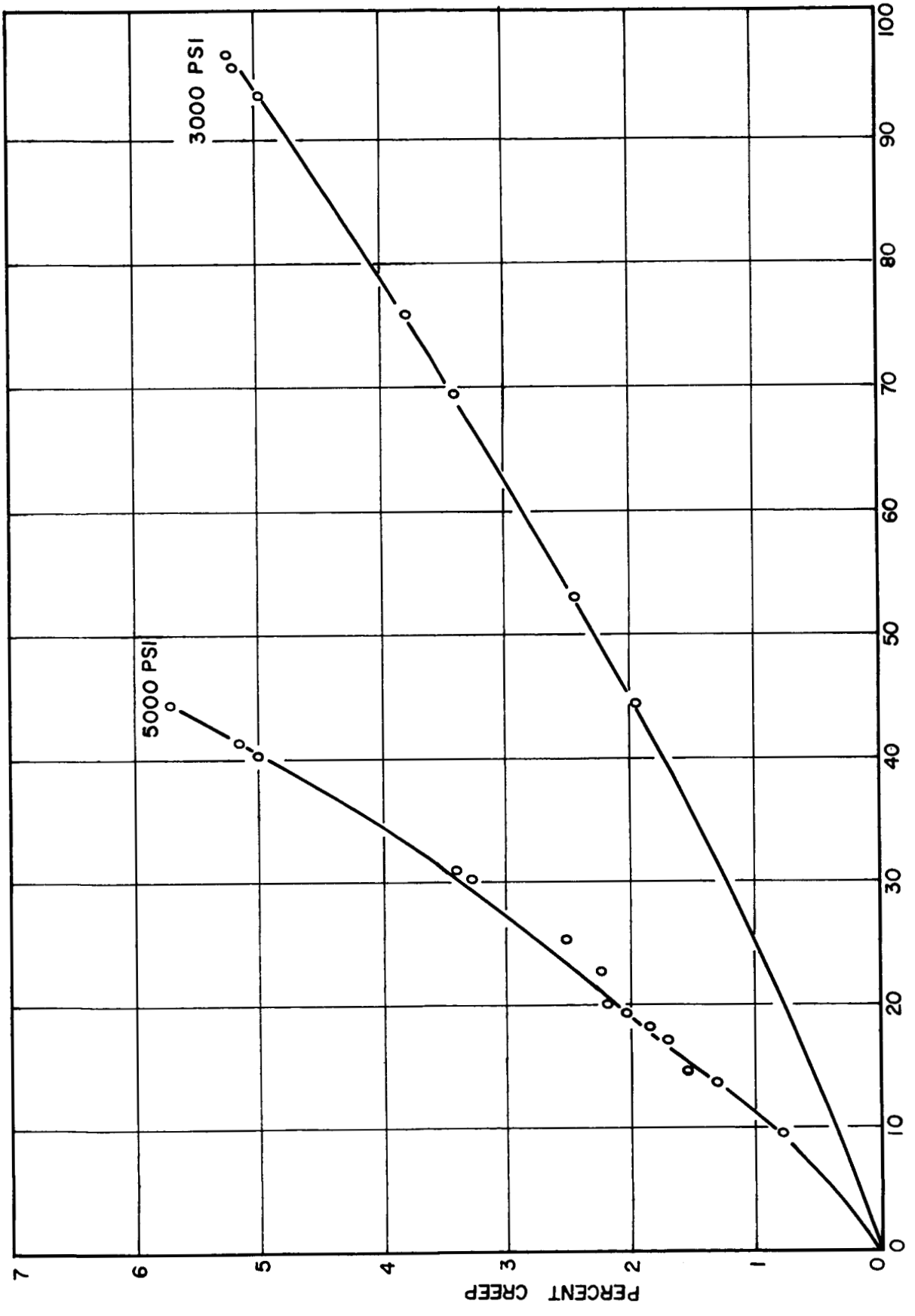


FIG. 1: CREEP OF RECRYSTALLIZED TUNGSTEN - 25% RHENIUM ALLOY TESTED AT 3200°F, $<1 \times 10^{-8}$ TORR VACUUM.

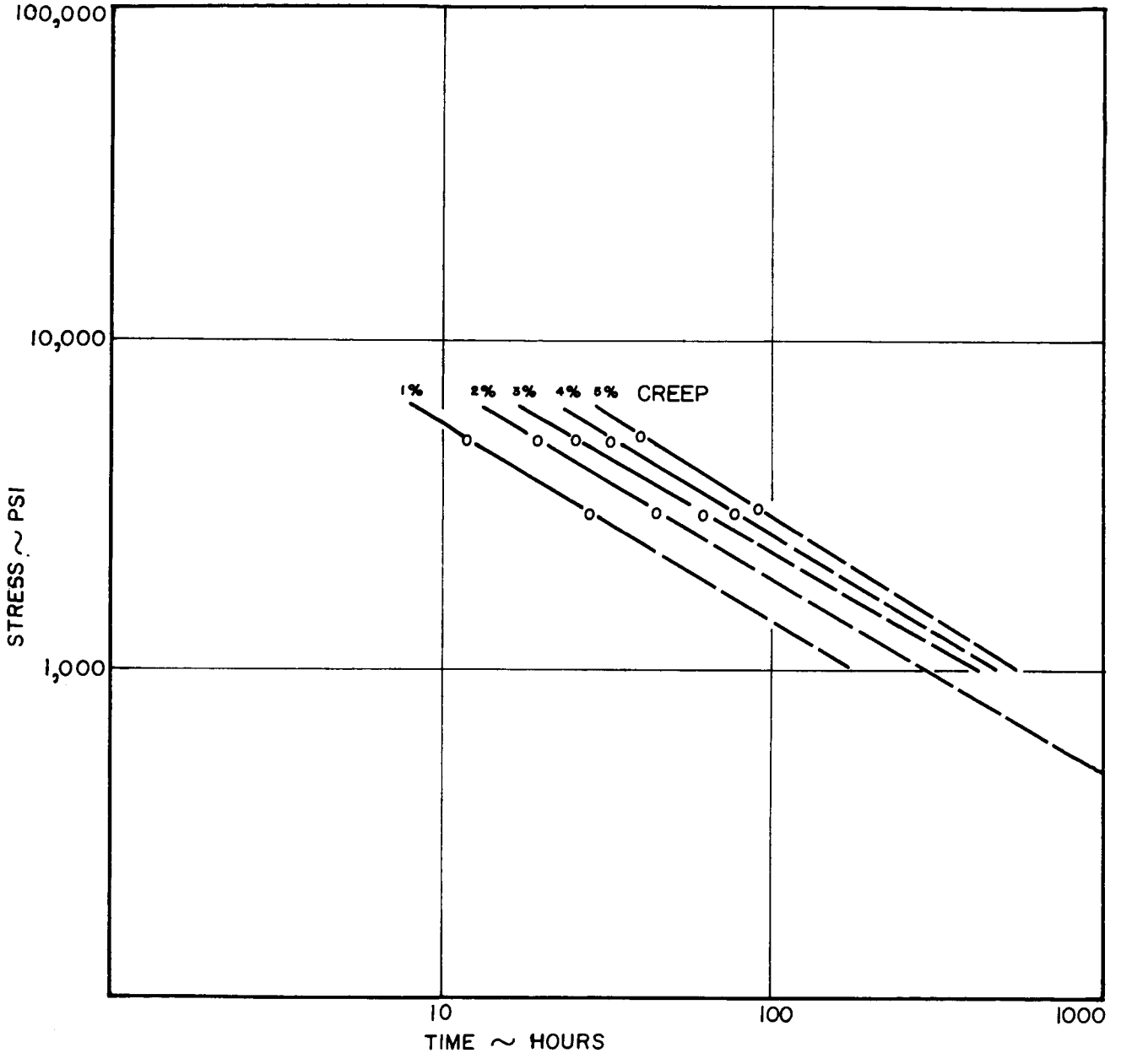


FIG. 2: RELATIONSHIP BETWEEN APPLIED STRESS AND TIME TO PRODUCE A GIVEN AMOUNT OF CREEP, RECRYSTALLIZED TUNGSTEN - 25% RHENIUM ALLOY, $<1X10^{-8}$ TORR VACUUM.

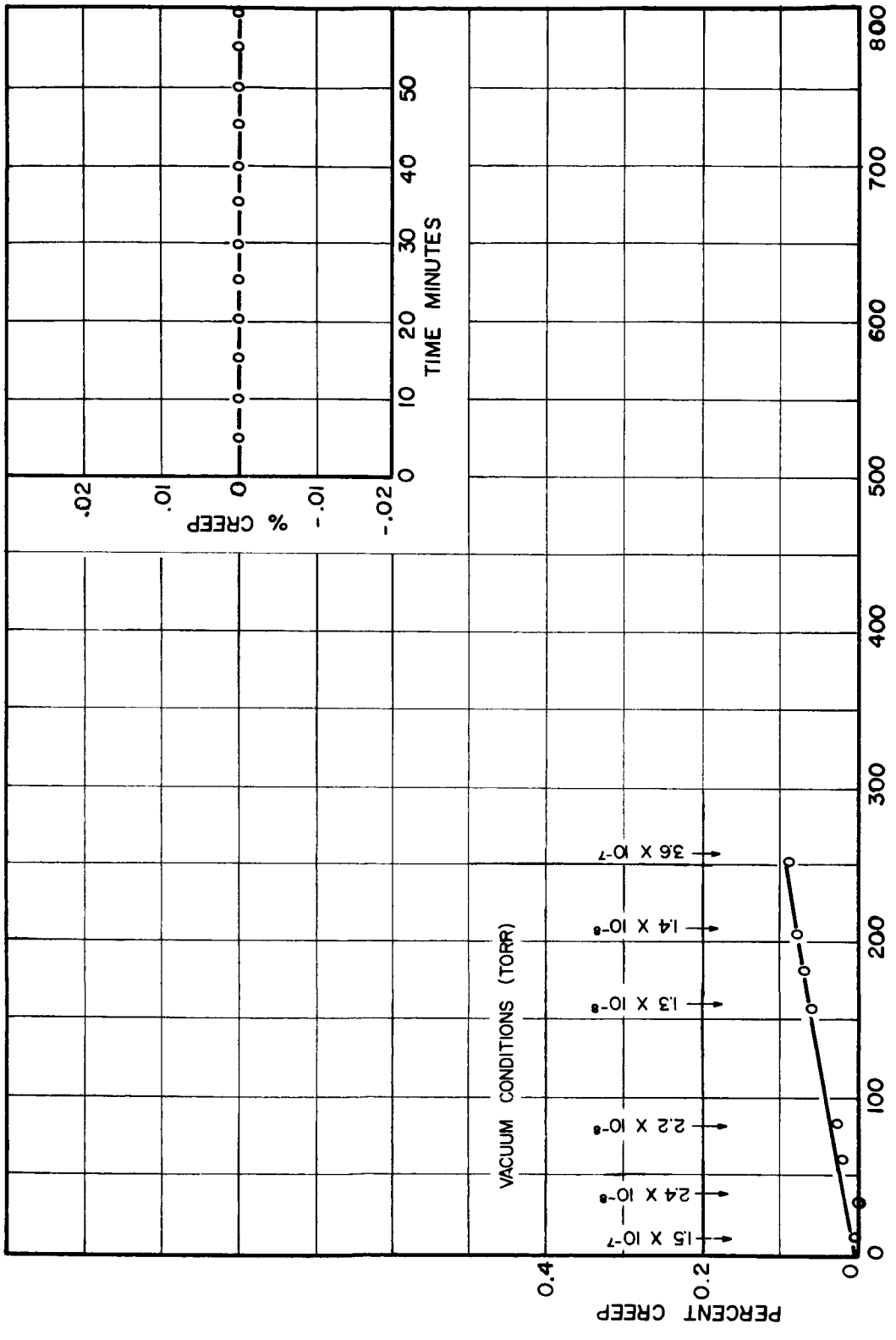
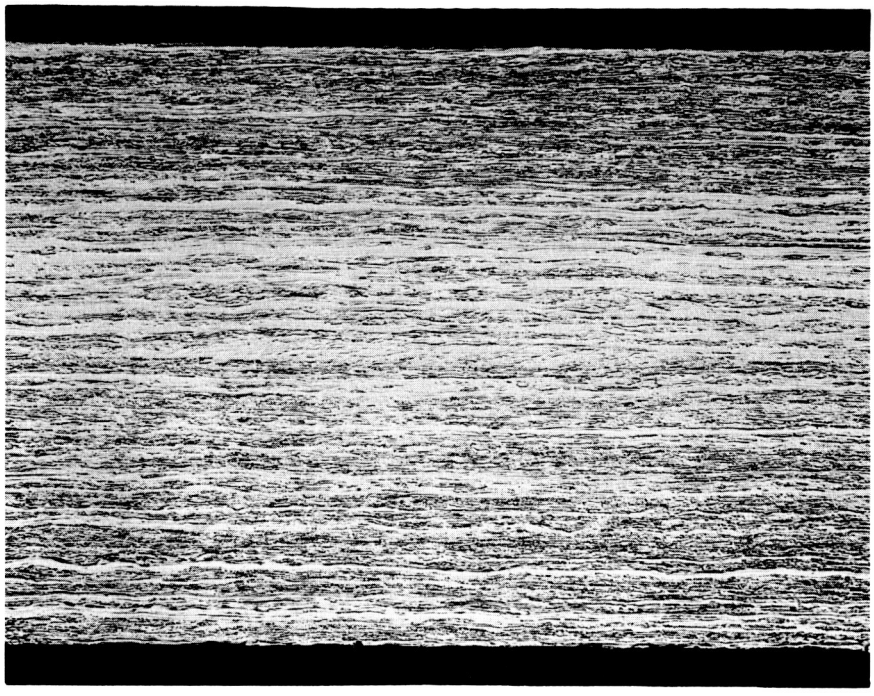
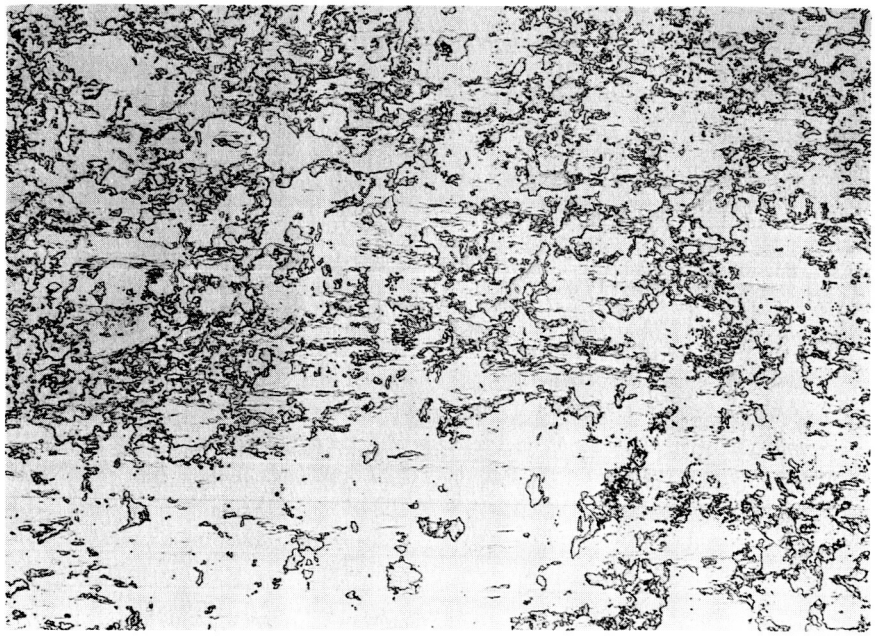


FIG. 3: CREEP OF RECRYSTALLIZED TUNGSTEN - 25% RHENIUM ALLOY TESTED AT 3200°F,



A 1574

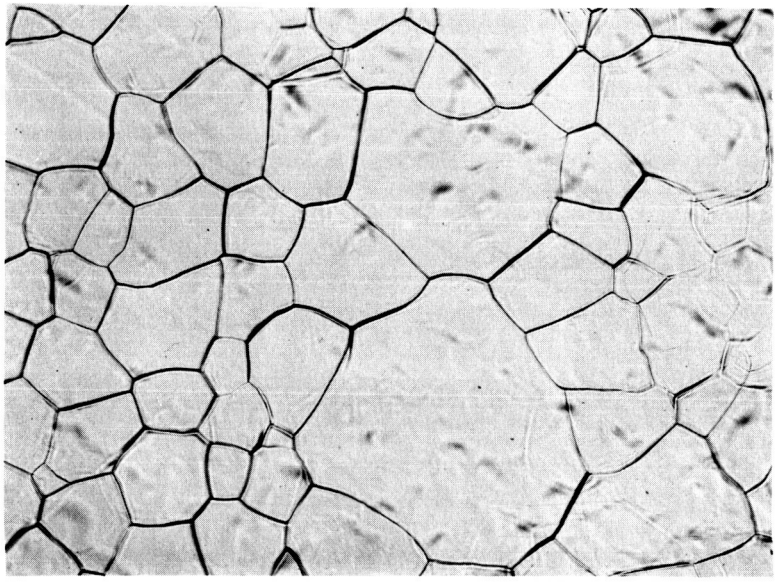
EDGE PERPENDICULAR TO ROLLING DIRECTION



A 1573

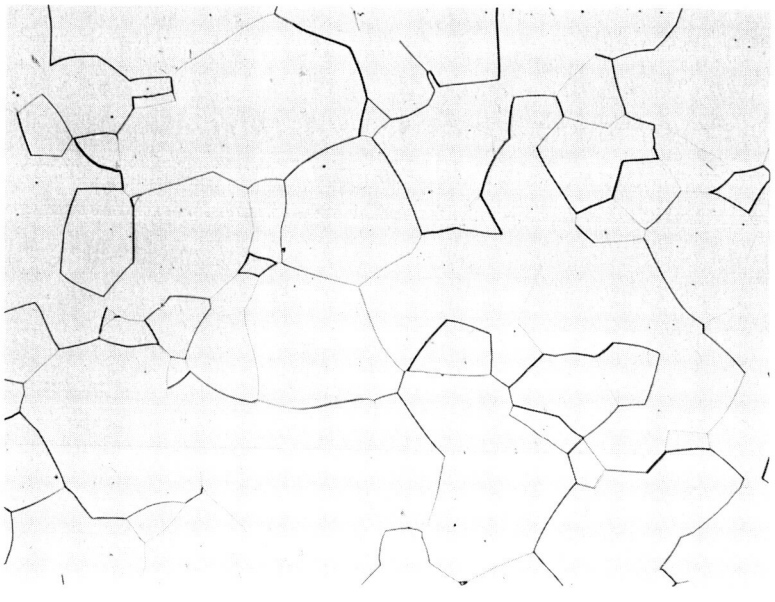
SURFACE OF SHEET

FIG. 4: MICROSTRUCTURE OF TUNGSTEN-25% RHENIUM ALLOY SHEET IN AS-RECEIVED CONDITION. ETCHANT: 15% HF, 15% H_2SO_4, 8% HNO_3, 62% H_2O, 100 X.



A 1786

UNPOLISHED SURFACE OF SPECIMEN SHOWING THERMAL ETCHING



A 1789

TYPICAL MICROSTRUCTURE AFTER POLISH & ETCH
ETCHANT: 15% HF, 15% H_2SO_4, 8% HNO_3, 62% H_2O

FIG.5: MICROSTRUCTURE OF TUNGSTEN-25% RHENIUM ALLOY AFTER TESTING AT 3200°F FOR 97 HOURS, 100X.

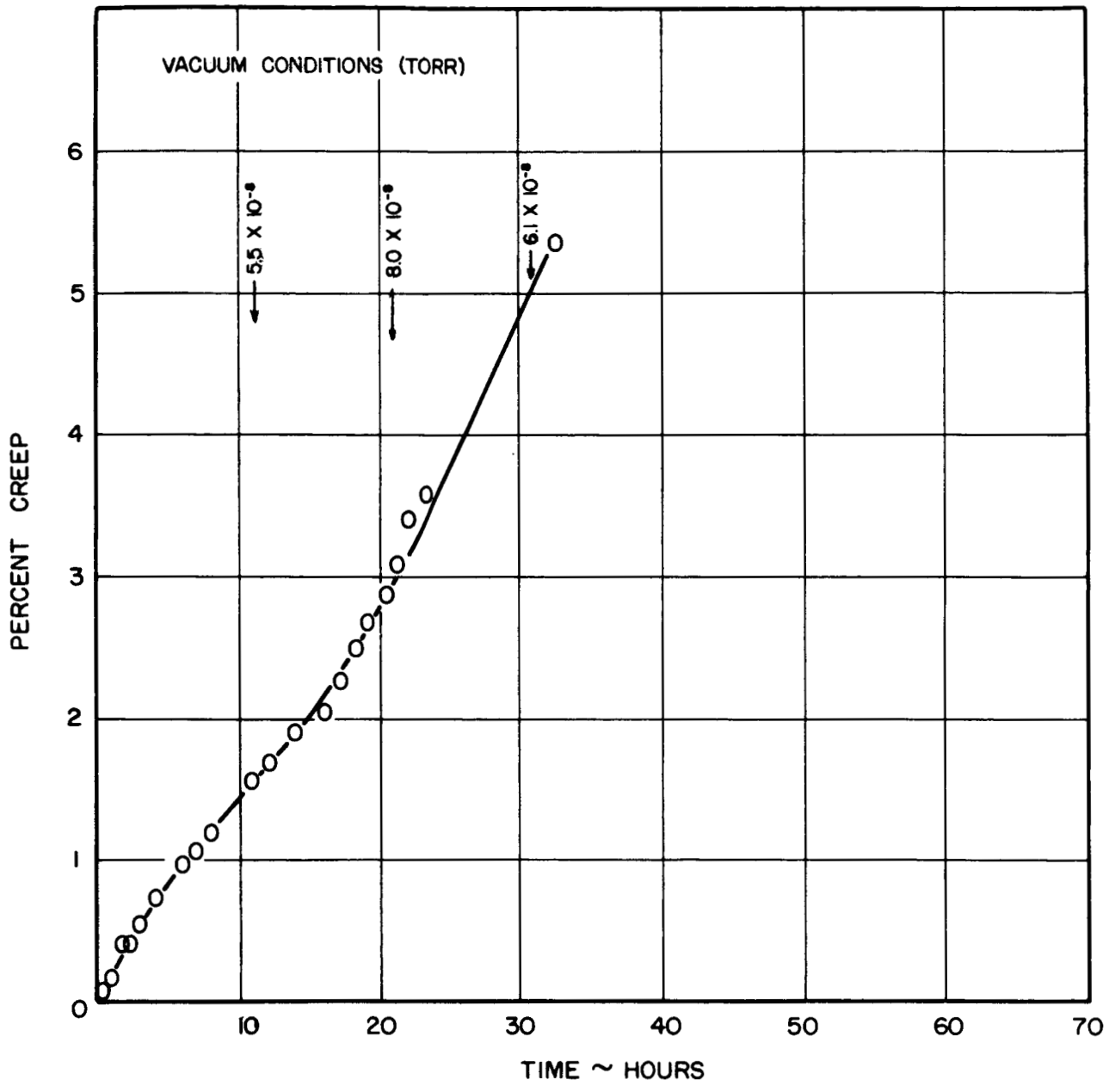


FIG. 6: CREEP OF RECRYSTALLIZED TUNGSTEN TESTED AT 3200° F, 3000 PSI.

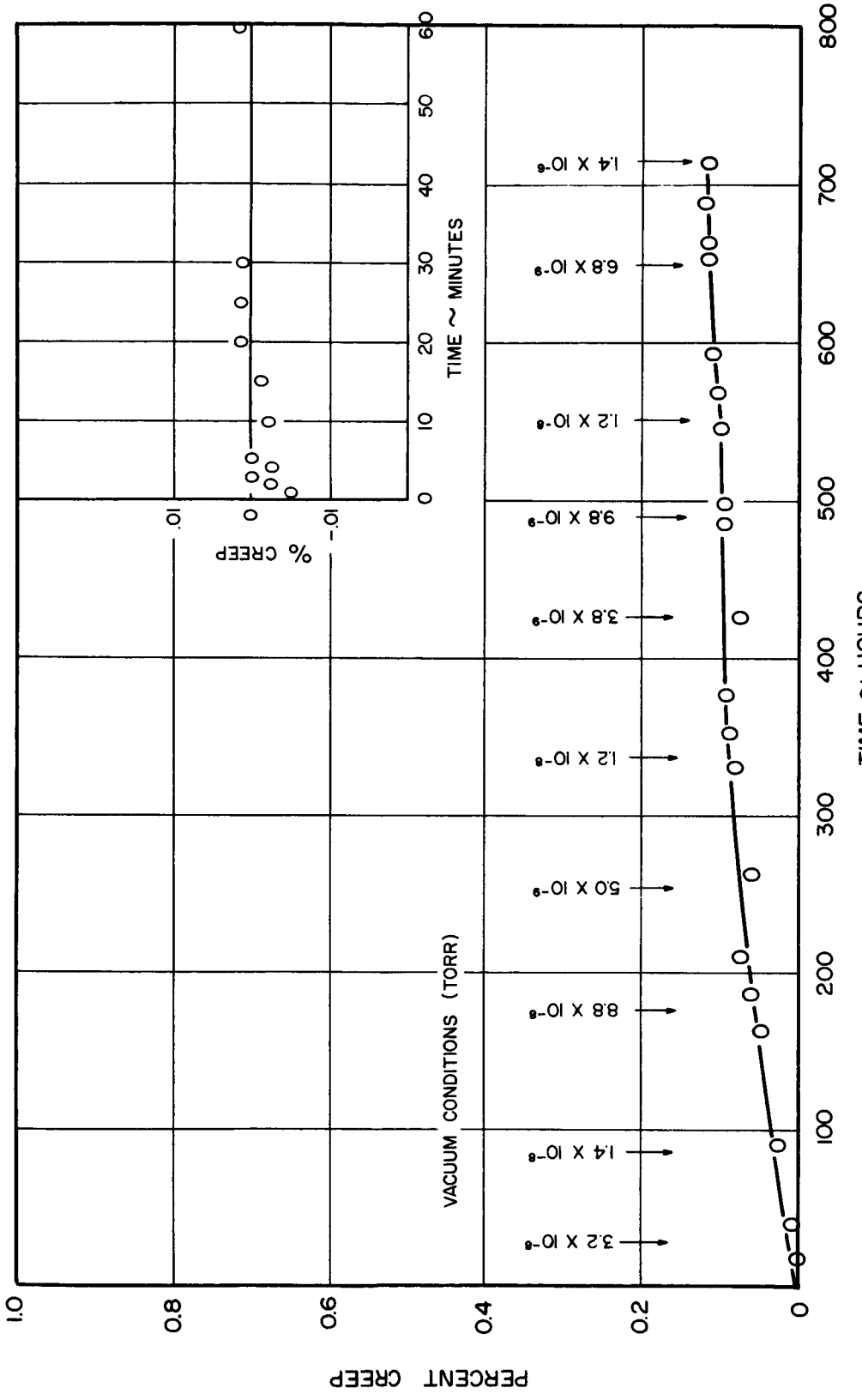
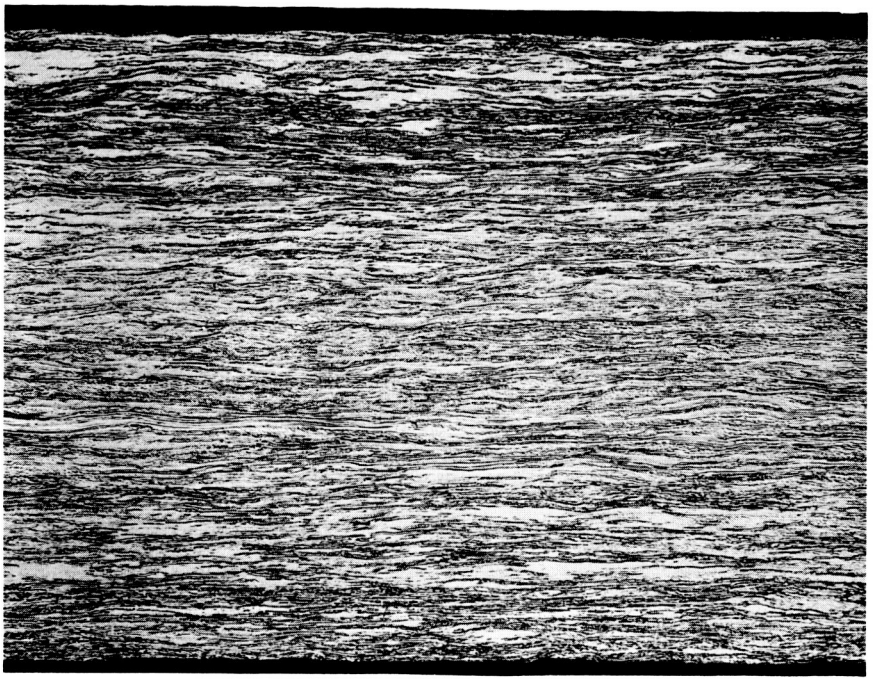


FIG. 7: CREEP OF RECRYSTALLIZED TUNGSTEN SHEET TESTED AT 3200°F, 400 PSI.



A 1577

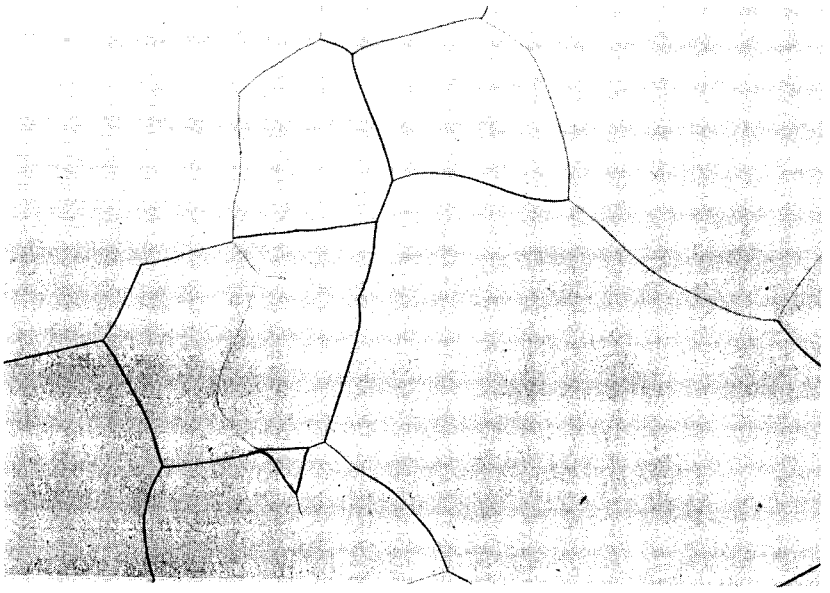
EDGE PERPENDICULAR TO ROLLING DIRECTION

A 1576

SURFACE OF SHEET

FIG. 8: MICROSTRUCTURE OF TUNGSTEN SHEET IN AS-RECEIVED CONDITION. ETCHANT: 15% HF, 15% H_2SO_4, 8% HNO_3, 62% H_2O, 100X.

7644



A 1790

TYPICAL MICROSTRUCTURE AFTER POLISH & ETCH

FIG. 9: MICROSTRUCTURE OF TUNGSTEN SHEET AFTER TESTING AT 3200°F, 714 HOURS, ETCHANT: 15% HF, 15% H_2SO_4, 8% HNO_3, 62% H_2O, 100X.

The available chemical analysis of the tungsten sheet is given in Appendix II, Table IX.

TZM Molybdenum Alloy

The first turbine alloy to be evaluated was TZM in the stress-relieved condition. A preliminary test was made with the objective of checking out the grip and specimen arrangement, determining the ability of the extensometer to measure elongation on a curved surface, and measuring the temperature gradient. The temperature of this test was not determined from a calibrated thermocouple as is the normal practice but was measured with an optical pyrometer corrected for sight port losses. The test temperature was 2130°F and the applied stress 12,555 psi. After 645 hours, a creep of 1% was produced and the test was terminated.

The data are presented in Figure 10, page 13, with the measurements taken during the first hour plotted in the insert. Data obtained from a second test which is now in progress at a temperature of 2000°F and 10,000 psi are given in Figure 11, page 14.

The test results in Figure 10 show that TZM exhibited a relatively rapid creep rate during the first 100-150 hours which was followed by a period where the creep rate decreased to a very low value. After approximately 450 hours, extension continually increased until the selected creep limit of 1% was reached.

The microstructure of the TZM alloy prior to testing is shown in Figure 12, page 15. The area parallel to a radius and perpendicular to the surface of the disc reveals extensive flow lines which are not uniform, but vary depending upon the area examined. The microstructure of the cross-section of the specimen (perpendicular to a radius of the disc forging) after 650 hours at 2130°F is shown in Figure 13, page 16. In contrast to the microstructure before testing this specimen shows definite flow lines probably residual from the upsetting process. The fact that they did not appear in the original microstructure is attributed to the position of the two areas examined with respect to the distance from the center of the forging. Additional examination will be made in an attempt to clarify this point. At present there is no evidence of microstructural change in the TZM alloy which could account for the rapid increase in creep rate that occurred after approximately 500 hours.

AS-30 Columbium Alloy

The initial test on AS-30 plate in the stress-relieved condition was conducted at 2000°F and 12,000 psi. The data plotted in Figure 14 indicate that the 1% creep limit was attained after 800 hours. The general progress of creep for the duration of the test was quite linear with the exception of the period at 100-150 hours, where a slight inflection appeared on the creep curve. A slight temporary rise in pressure (10^{-6} Torr range) was also noted during this time period.

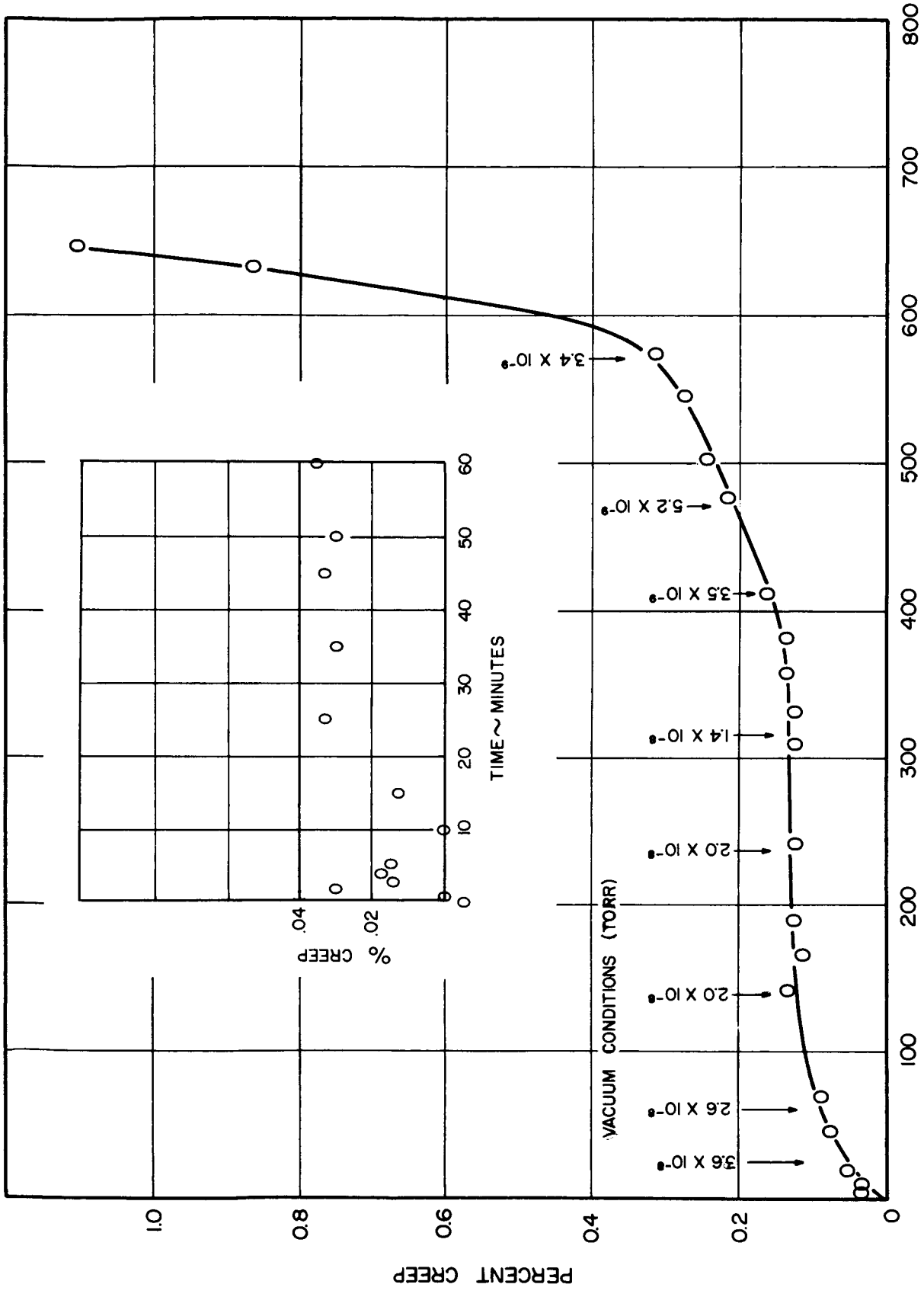


FIG. 10: CREEP OF STRESS-RELIEVED TZM TESTED AT 2130°F, 12,555 PSI.

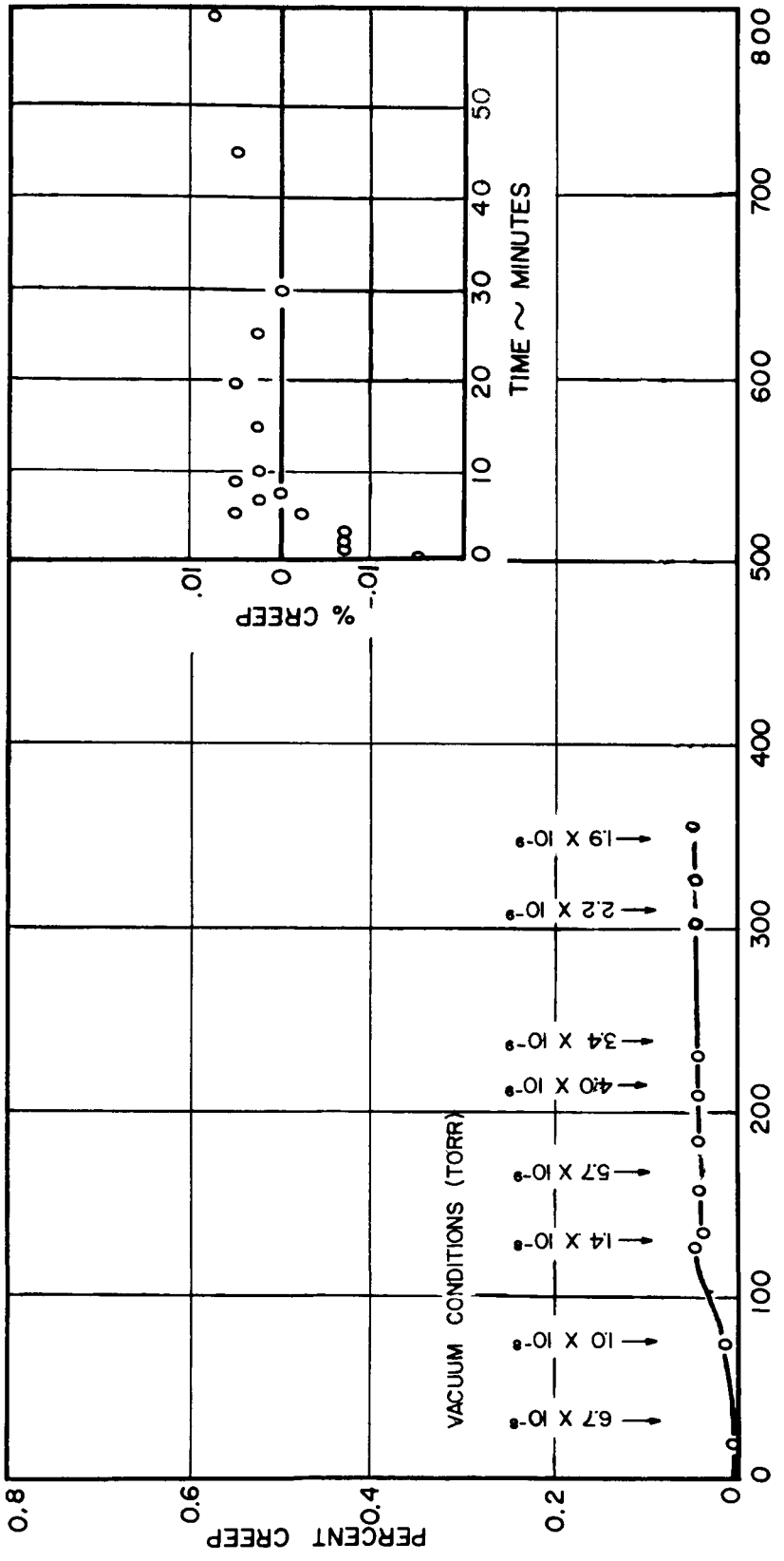
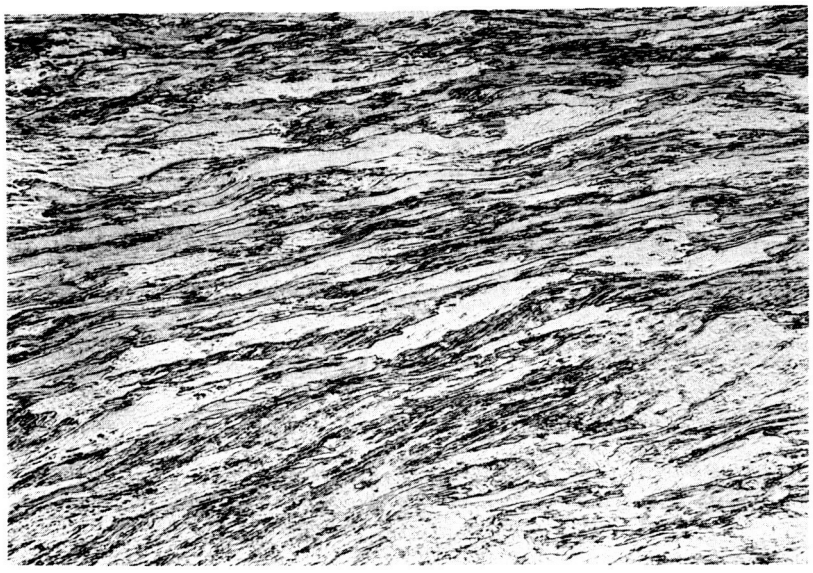
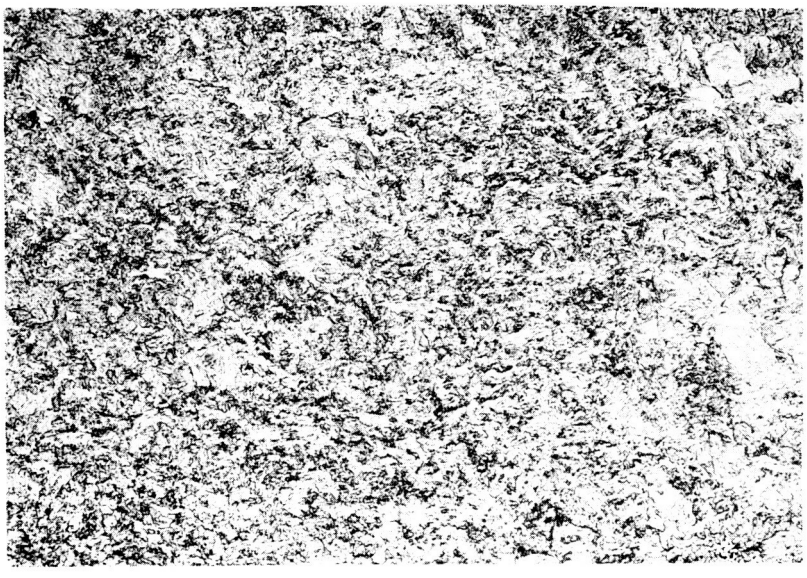


FIG. 11: CREEP OF STRESS-RELIEVED TZM TESTED AT 2000°F, 10,000 PSI.



A 1565

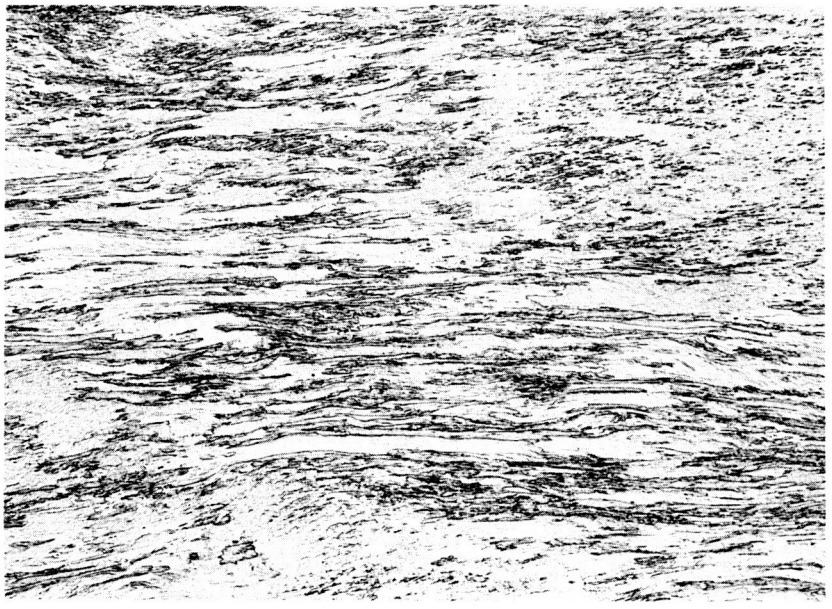
EDGE PARALLEL TO RADIAL DIRECTION



A 1563

EDGE PERPENDICULAR TO RADIAL DIRECTION

FIG. 12: MICROSTRUCTURE OF TZM FORGED DISC IN AS-RECEIVED CONDITION, MURAKAMI'S ETCH, 100X



A 1788

CROSS SECTION OF SPECIMEN
(EDGE PERPENDICULAR TO RADIAL DIRECTION)

FIG. 13: MICROSTRUCTURE OF TZM FORGED DISC AFTER 650 HOURS AT 2130°F, MURAKAMI'S ETCH, 100X

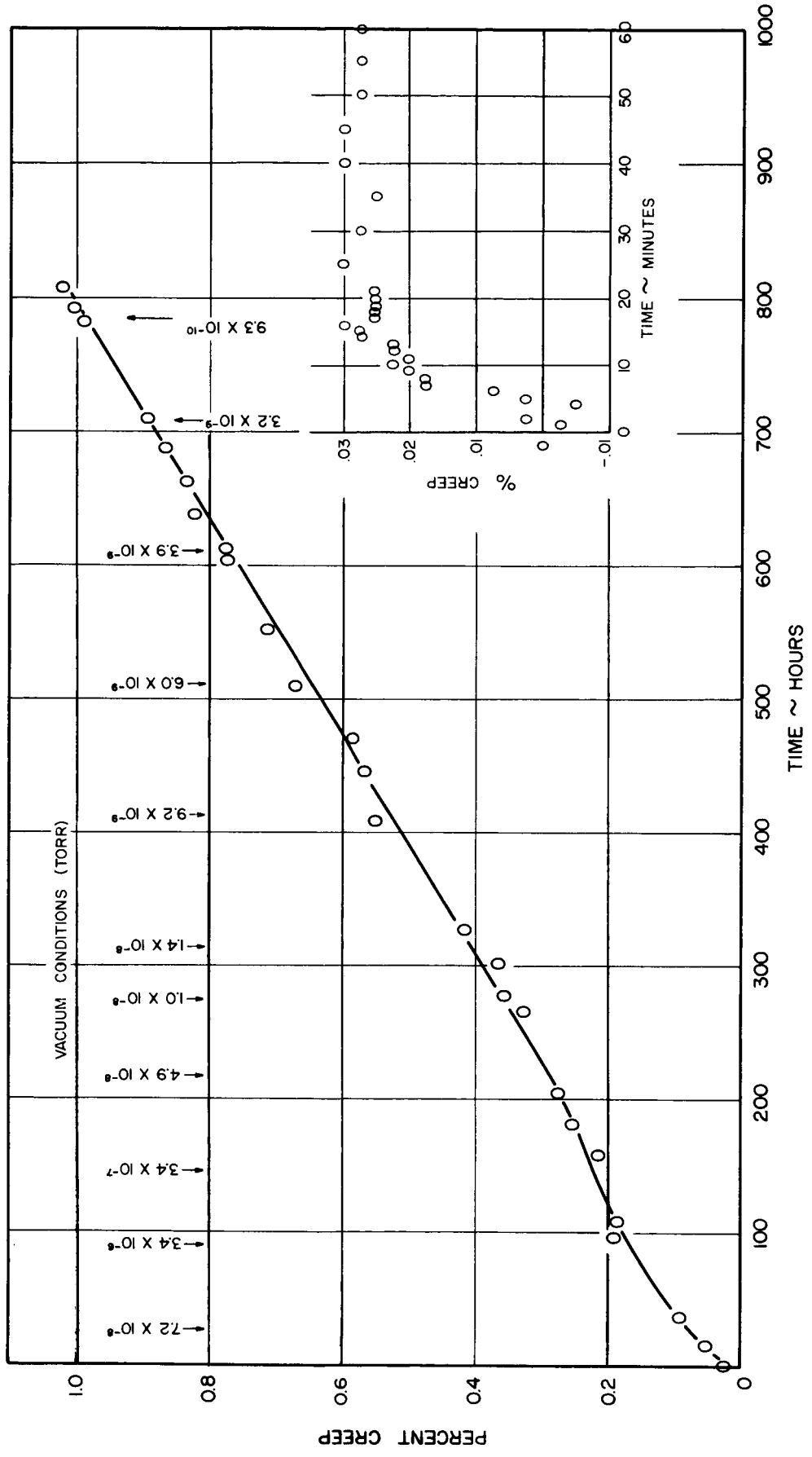


FIG. 14: CREEP OF STRESS - RELIEVED AS-30 TESTED AT 2000°F, 12000 PSI.

The microstructure of the as-received AS-30 plate is shown in Figure 15. Although cross rolling has to a large extent broken up the extruded structure, the surface of the plate does indicate that some slight directionality still persists. The microstructure of the specimen cross section (edge of plate parallel to the rolling direction) after 800 hours at 2000°F is shown in Figure 16. The structure indicates that little change has taken place as a result of exposure to the test conditions.

DISCUSSION

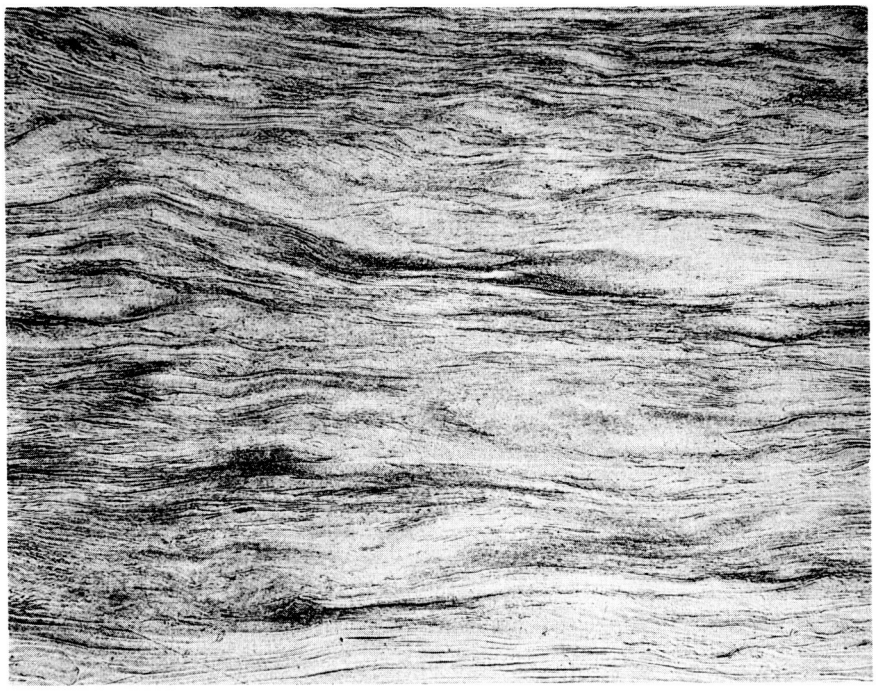
From the data available to date, some preliminary material comparisons can be made. In the case of the sheet alloys, tungsten-25% rhenium and tungsten at relatively high stress levels, the tungsten is less resistant to creep. This observation is based upon the fact that at 3200°F tungsten-25% rhenium with 5,000 psi stress reached the 5% creep limit in 40 hours whereas tungsten with a stress of 3,000 psi required only 31 hours to attain this same limit. At lower stresses the two materials are more comparable. Tungsten-25% rhenium at a stress of 500 psi required approximately 275 hours to reach 0.1% creep while tungsten at 400 psi required approximately 450 hours to attain this same degree of creep.

A comparison of the two turbine alloys TZM and AS-30 in the stress-relieved condition is somewhat difficult since they show two entirely different creep curves with the same test conditions. However, for total creep extensions below 0.5% the TZM alloy appears to be superior to the AS-30 material.

FUTURE WORK

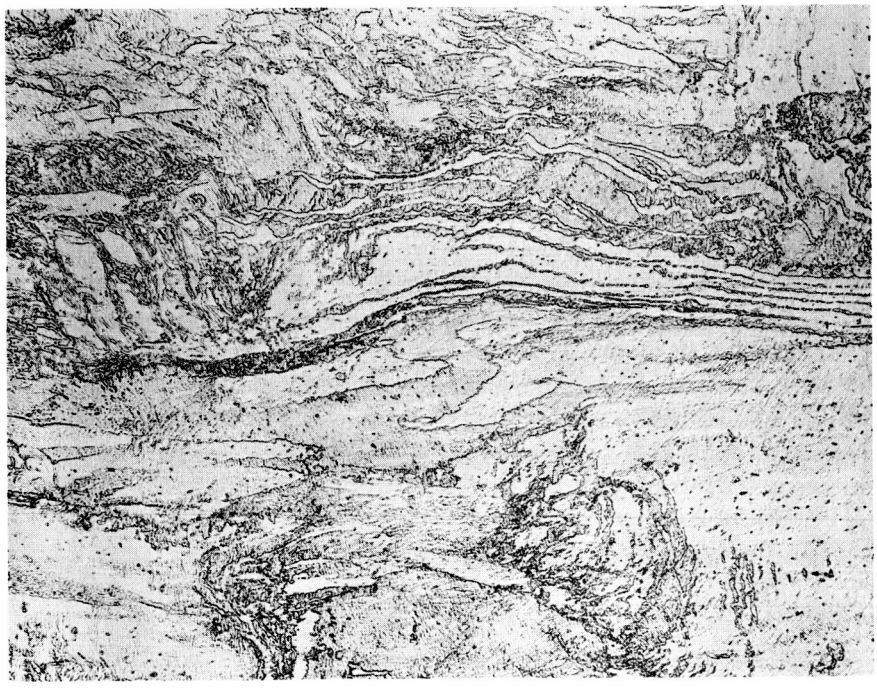
Testing will be initiated on the TZC alloy which is currently available. Both the ST222 and Cb132M should be received during the next quarter, and these materials will be integrated into the test program to provide comparative data for the turbine alloys.

The Sylvania A sheet material is scheduled for delivery within the next month. Creep curves will be determined to allow selection of the best cladding alloy for the 10,000 hour tests.



A 1578

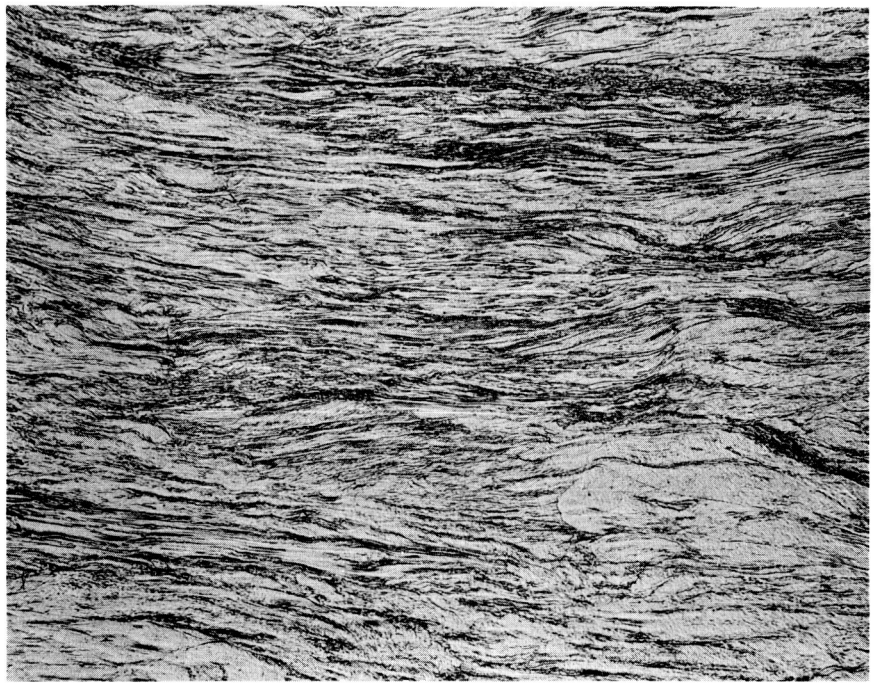
EDGE PARALLEL TO ROLLING DIRECTION



A 1580

SURFACE OF PLATE

FIG. 15: MICROSTRUCTURE OF AS-30 PLATE IN AS-RECEIVED CONDITION, ETCHANT: 15% HF, 15% H_2SO_4, 8% HNO_3, 62% H_2O, 100X.



A 1795

CROSS SECTION OF SPECIMEN

FIG. 16: MICROSTRUCTURE OF AS-30 PLATE AFTER 800 HOURS AT 2000°F, ETCHANT: 15% HF, 15% H_2SO_4, 8% HNO_3, 62% H_2O, 100 X.

APPENDIX I

TABLE A-I

PROCESSING OF TUNGSTEN - 25% RHENIUM SHEET

Vendor: Wah Chang Corporation
Albany Division

Processing History:

1) 0.055" sheet stress relieved one hour 2375°F
2) Rolled to 0.035"
3) 0.035" sheet stress relieved
   a) small sheet - 2375°F
   b) large sheet - 2550°F .

TABLE A-II

PROCESSING OF TUNGSTEN SHEET

Vendor: Universal Cyclops Steel Corporation
Bridgeville, Pennsylvania

Processing History:

1) Extruded 4:1 ratio 3100°F (TRW)
2) Forged open die 2200°F
3) Rolled
   a) Initial 2300°F
   b) Intermediate 1800°F
   c) Final 1400°F
4) Stress relieved 1700°F.

TABLE A-III

PROCESSING OF TZM FORGED DISC

Vendor: Climax Molybdenum Company of America
Coldwater, Michigan

Processing History:

1) Vacuum arc melted ingot 11-1/2" dia.
2) Machined to 10-3/4" dia.
3) Extruded to 6-1/4" dia.
4) Heat treated at 2700°F
5) Upset forged at 2200°F
6) Stress relieved at 2200°F

TABLE A-IV

PROCESSING OF AS-30 PLATE

Vendor: General Electric Company
Refractory Metals Plant

Processing History:

1) Vacuum arc melted ingot 5.4" dia.

2) Machined to 4.8" dia.

3) Jacket in molybdenum

4) Extrude 3.25:1 ratio at 2825°F to 4" x 1.625" sheet bar

5) Cross rolled at 2100°F to 0.790"; argon stmosphere

6) Acid etched to remove molybdenum jacket

7) Abrasive sawed to final width and length

TABLE A-V

PROCESSING OF TZC PLATE

Vendor: General Electric Company
Refractory Metals Plant
Cleveland, Ohio

Processing History:

1) Vacuum arc melted ingot 5.88" dia.,
2) Machine to 5" dia.,
3) Extrude 2:30:1 ratio to 4-1/8" x 2.22" sheet bar,
4) Cross-rolled at 2925°F in 4-1/8" direction to 0.740", hydrogen atmosphere,
5) Grit blasted and cut to final length with abrasive saw.

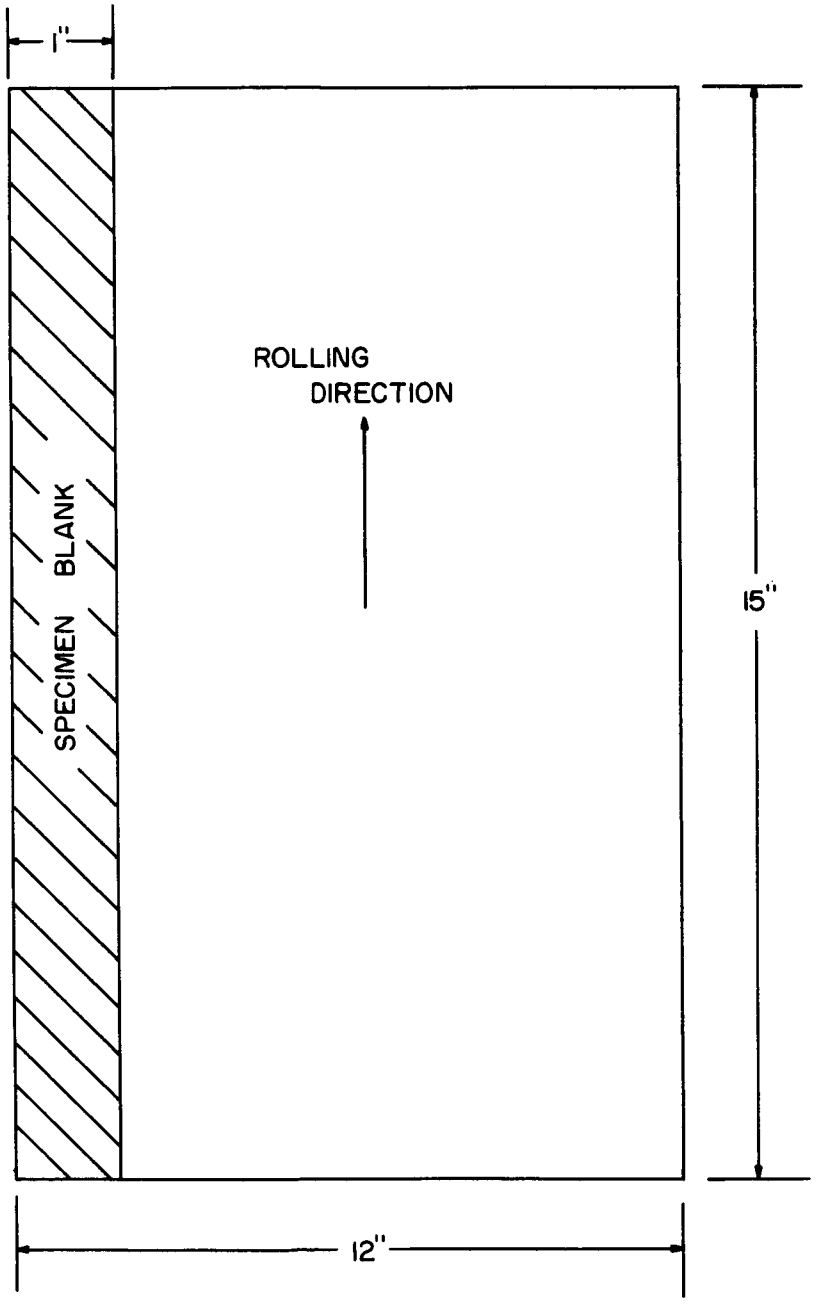


FIG. A-1 LOCATION OF SPECIMEN ON SHEET STOCK.

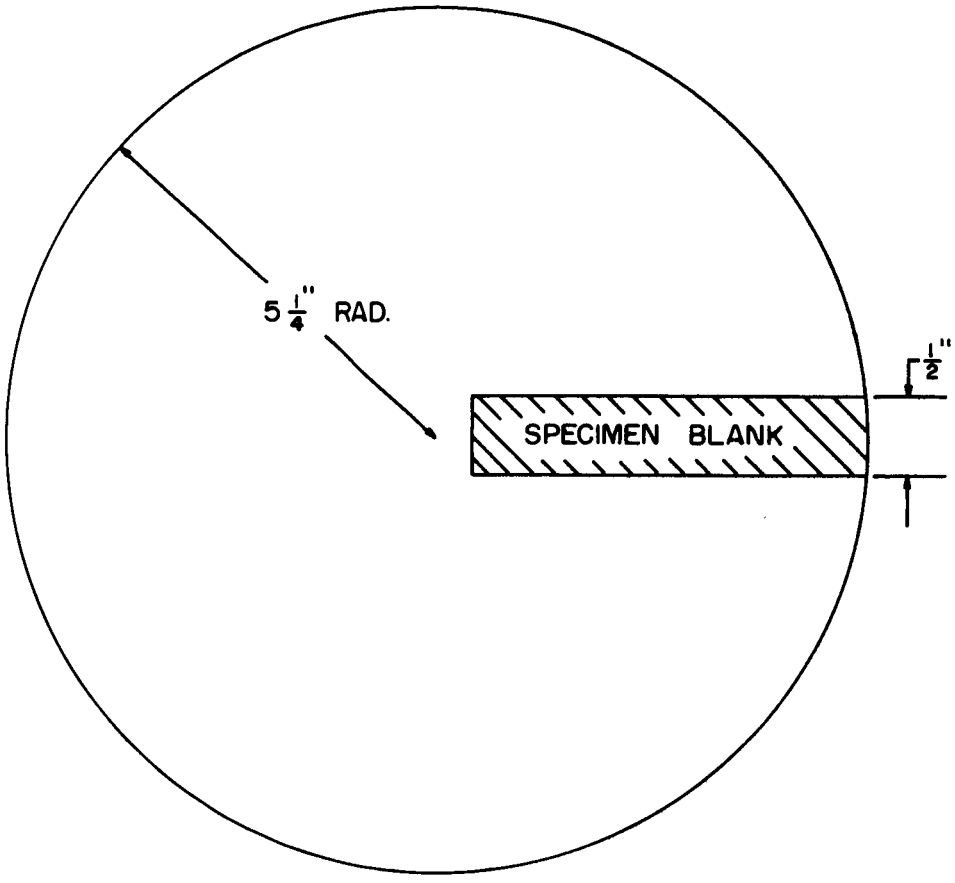


FIG. A-2 LOCATION OF SPECIMEN ON FORGED DISC.

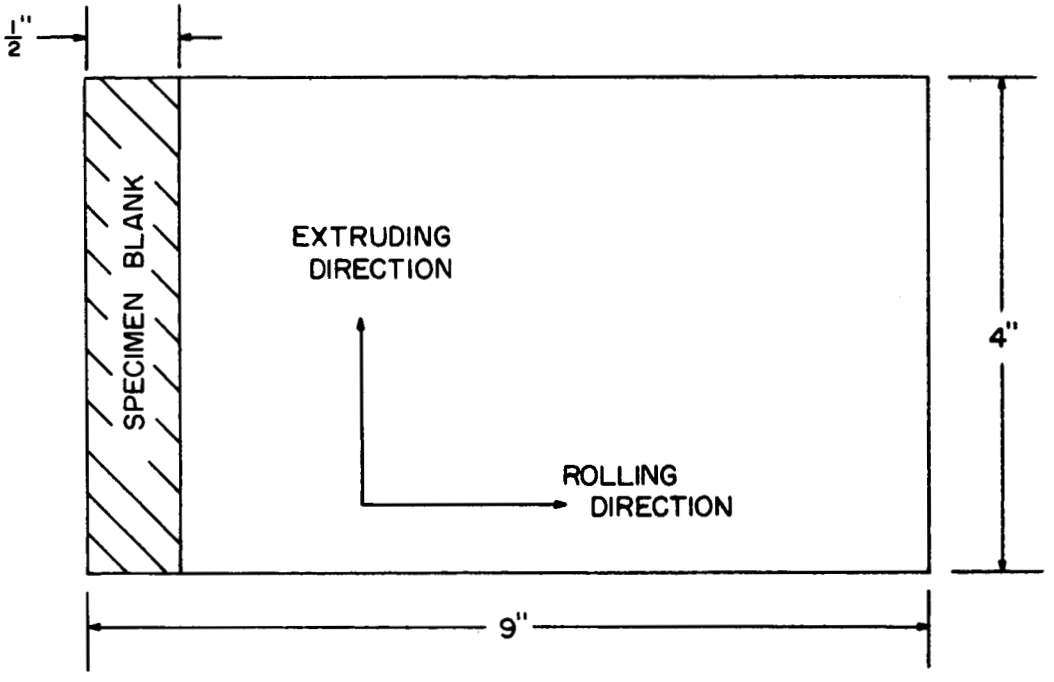


FIG. A-3 LOCATION OF SPECIMEN ON EXTRUDED AND ROLLED PLATE.

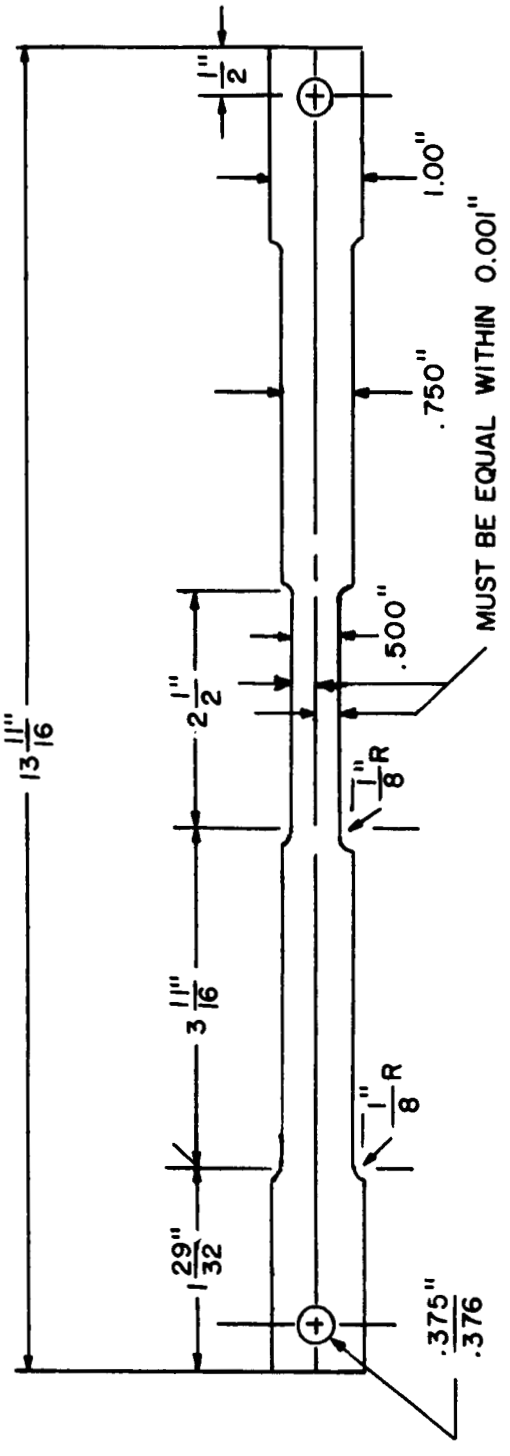
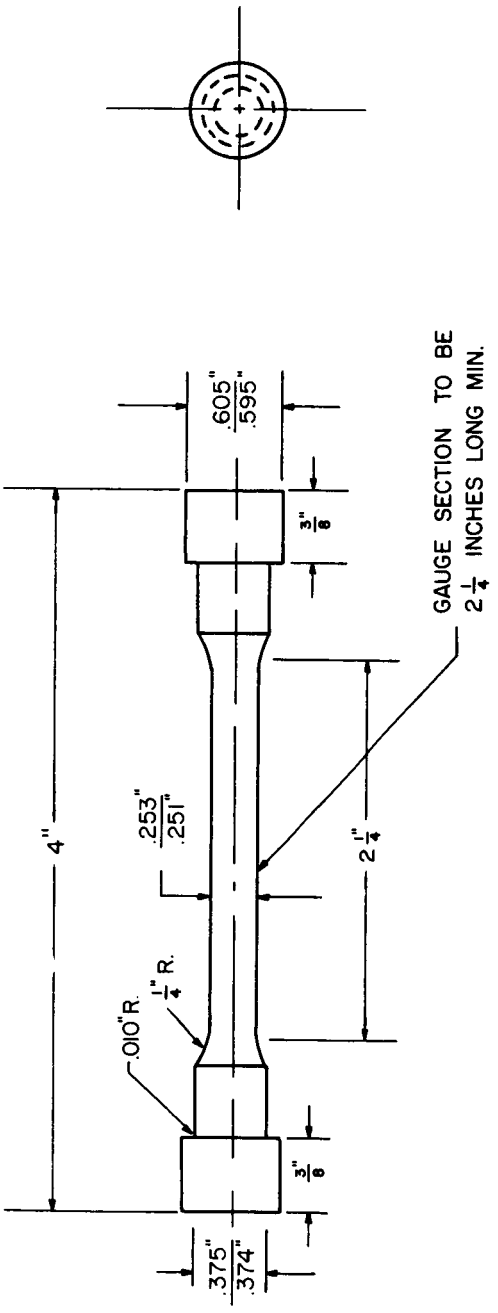


FIG. A-4 CREEP SPECIMEN USED FOR SHEET STOCK



NOTE: ANY TAPER IN GAUGE SECTION MUST BE TOWARDS CENTER

ALL TOLERANCES ± .010" UNLESS OTHERWISE NOTED

FIG. A-5 CREEP SPECIMEN USED FOR DISC AND PLATE STOCK.

APPENDIX II

TABLE B-I

CREEP TEST DATA, TUNGSTEN-25% RHENIUM SHEET*

3200°F, 3000 psi

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
.5	0	0	1×10^{-8}
1.0	.00015	.0075	
1.5	.00045	.0225	
2.0	.00075	.0375	
2.5	.00075	.0375	
3.0	.00090	.0450	
3.5	.00110	.0550	
44.4	.03945	1.972	6×10^{-9}
53.1	.04885	2.442	
68.6	.06780	3.39	7.8×10^{-9}
76.2	.07600	3.78	
93.7	.09930	4.96	8.4×10^{-9}
95.8	.10335	5.17	
**97.2	.10450	5.22	8×10^{-9}

* Alloy recrystallized in situ, approximately two hours at 3200°F, prior to load application.

** Test terminated at 5% creep limit.

TABLE B-II

CREEP TEST DATA, TUNGSTEN-25% RHENIUM SHEET*

3200°F, 500 psi

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
0.1	0	0	2.4×10^{-7}
0.2	0	0	
0.3	0	0	2.1×10^{-7}
0.4	0	0	
0.5	0	0	
0.6	0	0	
0.7	0	0	
0.8	0	0	
0.9	0	0	
1.0	0	0	1.9×10^{-7}
1.5	0	0	
2.0	0	0	1.5×10^{-7}
13.7	-.00005	-.0025	4.5×10^{-8}
37.1	0	0	2.4×10^{-8}
61.2	.00040	.0200	2.3×10^{-8}
85.3	.00050	.0250	2.2×10^{-8}
157.5	.00115	.0580	1.3×10^{-8}
182.7	.00140	.0700	1.3×10^{-8}
205.4	.00150	.0750	1.9×10^{-8}
**253.3	.00180	.0900	3.6×10^{-7}

* Alloy recrystallized in situ, approximately two hours at 3200°F, prior to load application.

** Test Terminated, leak in cold wall.

TABLE B-III

CREEP TEST DATA, TUNGSTEN SHEET*

3200°F, 3000 psi

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
.25	.00105	.05	8×10^{-7}
.50	.00199	.10	8×10^{-7}
.75	.00282	.14	8×10^{-7}
1.75	.00733	.37	7×10^{-7}
2.00	.00820	.41	6×10^{-7}
3.00	.01120	.56	5.5×10^{-7}
4.25	.01460	.73	2.2×10^{-6}
6.00	.01940	.97	1.2×10^{-6}
7.25	.02165	1.09	1.2×10^{-6}
8.00	.02385	1.20	7×10^{-7}
10.00	.02955	1.48	6×10^{-8}
11.00	.03150	1.58	5.5×10^{-8}
12.10	.03320	1.66	
13.90	.03780	1.89	
16.00	.04160	2.08	9×10^{-8}
17.00	.04500	2.26	9.3×10^{-8}
18.00	.04975	2.50	8.4×10^{-8}
19.00	.05395	2.70	7.9×10^{-8}
20.25	.05705	2.85	8.0×10^{-8}
21.00	.06165	3.08	7.8×10^{-8}
22.25	.06880	3.44	7.6×10^{-8}
23.00	.07140	3.57	7.5×10^{-8}
**32.30	.10778	5.38	6.1×10^{-8}

* Tungsten recrystallized in situ, approximately two hours at 3200°F, prior to load application.

** Test terminated at 5% creep limit.

TABLE B-IV

CREEP TEST DATA, TUNGSTEN SHEET*

3200°F, 400 psi

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)	Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	- .00010	.0050	2.6×10^{-7}	19.4	0	0	3.2×10^{-8}
2	- .00005	.0025		42.3	.00010	.005	1.7×10^{-8}
3	0	0		90.2	.00050	.025	1.4×10^{-8}
4	- .00005	.0025		163.1	.00100	.050	8.4×10^{-9}
5	0	0		186.3	.00125	.0625	8.8×10^{-9}
10	- .00035	.0018		210.4	.00145	.0725	1.5×10^{-8}
15	- .00020	.0010		234.9	.00120	.060	1.8×10^{-8}
20	.00030	.0015		258.3	.00100	.055	5.0×10^{-9}
25	.00030	.0015		264.5	.00120	.060	1.2×10^{-8}
30	.00025	.0013		330.5	.00160	.080	1.2×10^{-8}
60	.00025	.0013		354.4	.00180	.090	1.1×10^{-8}
				378.8	.00190	.095	6.0×10^{-9}
				426.4	.00145	.073	3.8×10^{-9}
				485.5	.00190	.095	4.6×10^{-9}
				498.8	.00195	.098	9.8×10^{-9}
				546.3	.00200	.100	6.9×10^{-9}
				569.7	.00210	.105	1.2×10^{-8}
				594.4	.00220	.110	8.8×10^{-9}
				654.9	.00230	.115	6.8×10^{-9}
				666.2	.00235	.118	6.6×10^{-9}
				690.8	.00240	.120	8.0×10^{-8}
				**714.2	.00235	.118	1.4×10^{-6}

* Tungsten recrystallized in situ, approximately two hours at 3200°F, prior to load application.

** Test terminated, leak in cold wall.

TABLE B-V

CREEP TEST DATA, STRESS-RELIEVED TZM FORGED DISC, 2128°F, 12,555 PSI

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	0	0	5×10^{-8}
2	.00060	.03	
3	.00030	.015	
4	.00035	.018	
5	.00030	.015	
10	0	0	
15	.00025	.013	
25	.00065	.033	
35	.00060	.030	
45	.00065	.033	
50	.00060	.030	
60	.00070	.035	

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	.00070	.035	
1.5	.00065	.033	
2.0	.00070	.035	
2.5	.00070	.035	
3.0	.00085	.043	
3.5	.00090	.045	
4.0	.00075	.038	
4.5	.00075	.038	
5.0	.00075	.038	
20.8	.00105	.053	3.6×10^{-8}
45.2	.00155	.078	3.0×10^{-8}
68.7	.00180	.090	2.6×10^{-8}
141.2	.00275	.138	2.0×10^{-8}
166.3	.00235	.118	2.4×10^{-8}
189.0	.00255	.128	2.1×10^{-8}
236.8	.00245	.123	2.0×10^{-8}
309.6	.00250	.125	1.4×10^{-8}
332.7	.00250	.125	1.3×10^{-8}
357.1	.00270	.135	1.2×10^{-8}
381.7	.00265	.133	1.2×10^{-8}
405.3	.00260	.130	3.5×10^{-9}
411.3	.00325	.163	9.0×10^{-9}
477.6	.00435	.218	5.2×10^{-9}
501.4	.00495	.248	5.1×10^{-9}
549.2	.00555	.278	5.0×10^{-9}
573.2	.00635	.318	3.4×10^{-9}
631.9	.01725	.863	3.3×10^{-9}
*645.7	.02210	1.105	4.6×10^{-9}

* Test Terminated at 1% creep limit.

TABLE B-VI

CREEP TEST DATA, STRESS-RELIEVED TZM FORGED DISC, 2000°F, 10,000 PSI

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	-.00030	-.015	1.6×10^{-7}
2	-.00015	-.0075	
3	-.00015	-.0075	
4	-.00015	-.0075	
5	-.00005	-.0025	
6	.00010	.005	
7	.00005	.0025	
8	.0000	.000	
9	.00010	.005	
10	.00005	.0025	
15	.00005	.0025	
20	.00010	.005	
25	.00005	.0025	
30	.00000	.0000	
45	.00010	.005	
60	.00015	.0075	
75	.00005	.0025	
90	.00010	.005	

Time (Hours)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
20.0	-.00005	-.0025	6.7×10^{-8}
74.7	.00030	.015	1.0×10^{-8}
125.7	.00100	.05	1.4×10^{-8}
136.5	.00080	.04	1.0×10^{-8}
160.3	.00085	.0425	5.7×10^{-9}
184.4	.00085	.0425	4.4×10^{-9}
208.5	.00090	.045	4.0×10^{-9}
232.2	.00090	.045	3.4×10^{-9}
304.4	.00100	.05	2.2×10^{-9}
328.3	.00100	.05	2.0×10^{-9}
352.3	.00105	.0525	1.9×10^{-9}
376.6	.00105	.0525	1.3×10^{-9}

TABLE B-VII

CREEP TEST DATA, STRESS-RELIEVED AS-30 PLATE, 2000°F, 12,000 PSI

Time (Minutes)	Length Change ΔL (in) (2" G. L.)	Creep (%)	Pressure (Torr)
1	-.00005	-.0025	3.4×10^{-7}
2	.00005	.0025	
4	-.00010	-.005	
5	.00005	.0025	
6	.00015	.0075	
7	.00035	.0175	
8	.00035	.0175	
9	.00040	.020	
10	.00045	.0225	
11	.00040	.020	
12	.00045	.0225	
13	.00045	.0225	
14	.00055	.0275	
15	.00055	.0275	
16	.00060	.030	
17	.00050	.025	
18	.00050	.025	
19	.00050	.025	
20	.00050	.025	
21	.00050	.025	
25	.00060	.030	
30	.00055	.0275	
35	.00050	.025	
40	.00060	.030	
45	.00060	.030	3.2×10^{-7}
50	.00055	.0275	
55	.00055	.0275	
60	.00055	.0275	
17.8	.00110	.055	7.2×10^{-8}
38.4	.00190	.095	4.4×10^{-8}
97.2	.00380	.190	3.4×10^{-6}
110.8	.00380	.190	2.2×10^{-6}
158.2	.00435	.2175	3.4×10^{-7}
182.7	.00515	.2575	9.4×10^{-8}
206.4	.00545	.2725	4.9×10^{-8}
266.4	.00655	.3275	1.2×10^{-8}
278.2	.00705	.3525	1.0×10^{-8}
302.7	.00725	.3625	1.4×10^{-8}
326.2	.00830	.415	7.5×10^{-9}
410.4	.01100	.55	9.2×10^{-9}
446.6	.01125	.5625	9.2×10^{-9}
470.9	.01165	.5825	5.8×10^{-9}
510.1	.01345	.6725	6.0×10^{-9}
552.7	.01430	.715	4.4×10^{-9}
603.8	.01545	.7725	3.9×10^{-9}
614.4	.01555	.7775	4.8×10^{-9}
638.4	.01645	.8225	5.4×10^{-9}
662.5	.01675	.8375	4.0×10^{-9}
686.6	.01735	.8675	3.6×10^{-9}
710.3	.01785	.8925	3.2×10^{-9}
782.4	.01980	.990	1.8×10^{-9}
790.9	.02015	1.0075	9.3×10^{-10}
*806.4	.02045	1.0225	1.6×10^{-9}

* Test Terminated at 1% creep limit.

TABLE B-VIII

CHEMICAL ANALYSIS* OF TUNGSTEN-25% RHENIUM SHEET

(Weight Percent)

Element	Vendor Certification		TRW Analysis 3200°F - 97 Hrs.
	Top	Bottom	
Al	< 0.0020	< 0.0020	< 0.005
B	< 0.0001	< 0.0001	--
C	0.0050	0.0030	0.006
Cb	0.0100	0.0150	< 0.010
Cd	< 0.0005	< 0.0005	--
Co	0.0020	< 0.0100	--
Cr	< 0.0020	< 0.0020	< 0.010
Cu	< 0.0040	< 0.0040	< 0.010
Fe	0.0100	0.0115	< 0.010
H_2	0.00014	0.00014	0.0005
Mg	< 0.0020	< 0.0020	--
Mn	< 0.0020	< 0.0020	< 0.010
Mo	0.0300	0.0250	< 0.02
N_2	0.0040	0.0030	0.001
Ni	< 0.0020	< 0.0020	< 0.010
O_2	< 0.0050	< 0.0050	0.001
Pb	< 0.0020	< 0.0020	--
Re	25.1	26.0	24.90
Si	< 0.0100	< 0.0100	< 0.015
Sn	< 0.0020	< 0.0020	--
Ta	--	--	< 0.010
Ti	< 0.0020	< 0.0020	< 0.005
V	< 0.0020	< 0.0020	--
W	Bal.	Bal.	Bal.
Zn	0.0050	< 0.0050	--

* TRW Analysis on as-received material not completed.

TABLE B-IX

CHEMICAL ANALYSIS OF TUNGSTEN SHEET

(Weight Percent)

Element	Vendor Certification	TRW Analysis As-Received	TRW Analysis 3200°F - 32 Hrs.
Al	--	< 0.005	< 0.005
C	0.0020	-- *	0.036 **
Cb	--	< 0.010	
Cr	--	< 0.010	< 0.01
Cn	--	< 0.010	< 0.01
Fe	0.0006	< 0.010	< 0.01
H_2	0.00014	-- *	0.0005
Mn	--	< 0.015	< 0.01
Mo	0.0061	< 0.020	< 0.02
N_2	0.0011	-- *	0.001
Ni	0.0004	< 0.010	< 0.01
O_2	0.0010	-- *	0.001
Si	< 0.0020	< 0.015	< 0.01
Ta	--	< 0.010	< 0.01
Ti	< 0.0001	< 0.005	< 0.005
W	Balance	Balance	Balance

* Analysis not completed.

** Analysis to be rechecked.

TABLE B-X

CHEMICAL ANALYSIS TZM FORGED DISC

(Weight Percent)

Element	Vendor Certification
Al	< 0.001
C	0.013
Cb	< 0.005
Co	< 0.001
Cr	< 0.001
Cu	< 0.001
Fe	< 0.001
H_2	< 0.0001
Mg	< 0.001
Mn	< 0.001
Mo	Balance
N_2	0.0011
Ni	< 0.001
O_2	< 0.0002
Pb	< 0.001
Si	< 0.002
Sn	< 0.001
Ti	0.47
V	< 0.001
Zr	< 0.091

TABLE B-XI

CHEMICAL ANALYSIS AS-30 PLATE

(Weight Percent)

Element	Vendor Certification
C	0.0645 - 0.0655
Cb	Balance
Co	< 0.0100
Cu	< 0.0100
Fe	< 0.0100
H_2	< 0.0003 - 0.0006
Mn	< 0.0100
Mo	< 0.0200
N_2	0.0141 - 0.0173
Ni	0.0200
O_2	0.0130 - 0.0160
Pb	0.0050
Si	0.0200
Ti	0.0300
V	0.0150
W	20.16 - 20.34
Zr	0.90 - 0.98